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Validation of the Influence of Cation-Exchange Capacity on Resistivity Logs

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ABSTRACT

Resistivity models based on TEM (Transient Electro Magnetic) and MT (Magneto Telluric) soundings are widely used in geothermal exploration to select sites for exploration drilling. Resistivity models within high-temperature geothermal fields (e.g. Nesjavellir, southwest Iceland) mimic the dominant alteration mineralogy conditions in the subsurface. Thereby the typical observed boundary between the low-resistivity cap and the underlying high-resistive core in high-temperature systems can be related to changes in the secondary mineral inventory which have different cation-exchange capacity (CEC), i.e. from smectite dominated cap rock to the chlorite dominated core (Árnason et al 1987a; Árnason and Flóvenz 1992).

Alteration minerals with a high CEC favour the conduction of an electrical current between the pore fluid and the pore walls in the rock. This interface or surface conduction is caused by highly mobile ions that form a conductive layer on the surface of the pore walls. The mobility of ions is thereby related to the CEC of the mineral phase (Flóvenz et al 2012).

CEC measurements were conducted on drill cuttings in the Krafla and Hellisheidi geothermal fields in Iceland. High CEC values are associated with the clay dominated alteration zone and can be used as proxy for the degree and type of alteration of the volcanic succession. Thereby the CEC reflects the change in clay mineralogy with depth. Rock samples within the smectite alteration zone yield the highest CEC, whereas rocks within the chlorite zone and the epidote-actinolite zone result in a significant lower CEC and corresponding lower conductivity. The CEC, resistivity logs and temperature profile are compared to quantify the degree of physical and chemical parameters that control the electrical conductivity. This allows us to quantify the direct influence of each of those parameters on the electric resistivity.

1. INTRODUCTION

The typical resistivity structure of the Nesjavellir high-temperature geothermal reservoir in southwest Iceland shows a high-resistivity core beneath a low-resistivity cap based on 2D interpretation of a detailed multimethod DC resistivity surveys conducted in 1985 and 1986 Árnason et al (1987b). Figure 1 shows the alteration minerals in three wells and the isotherms derived from the estimated formation temperature in each well based on numerous temperature logs obtained during and after drilling of the geothermal wells. The figure shows a very clear correlation between the subsurface resistivity structure, on the one hand, and the alteration mineralogy and true formation temperature, on the other hand. The relation between the resistivity model and the alteration mineralogy is thought to be directly linked to the cation exchange capacity of the secondary minerals within the geothermal system (Flóvenz et al 2012).

Mineral that exhibit a high CEC favor the conduction of an electrical current between the pore fluid and the mineral surface. This interface or surface conduction is caused by the highly mobile ions that form a conductive layer on the surface of the pore walls. The higher the CEC for clay minerals the higher the interface conduction. Nevertheless, electrical conductivity can also be affected by other parameters: (i) degree of fluid saturation, (ii) conductivity of the rock matrix, (iii) salinity of the pore fluid, (iv) water–rock interaction and alteration mineral assemblage, (v) temperature, (vi) porosity and pore structure of the rock, and (vii) type of pore fluid like the content of water, steam, gas, and oil (Flóvenz et al 2012).

The aim of this task within the Integrated Methods for Advanced Geothermal Exploration (IMAGE) project is to assess the sensitivity of exploration techniques by a quantitative link between chemical properties of fluid/rock and electrical resistivity.

Three wells from two geothermal fields in Iceland had been selected to compare the resistivity logs with CEC values. Well KJ-18 (2215 m measured depth) in the Krafla high-temperature geothermal field in northeast Iceland was selected. Several resistivity logs have been carried out in well KJ-18, including resistivity time series during heating of the well. In addition, two wells (HE-42 and HE-46) from the Hellisheidi geothermal system within the Hengill volcanic system in southwest Iceland are selected. Well HE-46 (2744 m measured depth) was selected as it exhibits a well-defined low-resistivity cap (Haraldsdóttir and Franzson 2011) and the fact that the stratigraphy and alteration was worked out in detailed by an intense petrographic and mineralogical study (Snæbjörnsdóttir 2011) that results in a very good record of the hydrothermal alteration. Well HE-42 (3322 m measured depth) was selected as in contrast to well HE-46 the low-resistivity cap shows a larger degree of variation. The stratigraphy and alteration for the well were refined by Gunnarsdóttir (2012), resulting in a detailed record of the alteration.

Wells from the Krafla and the Hellisheidi geothermal systems had been selected for this study due to the low-salinity of the reservoir fluids, in contrast to the high-salinity geothermal fields on Reykjanes, to minimize the salinity effect on the resistivity log. Further studies on the Reykjanes geothermal field and the relation of CEC and electrical resistivity are in progress.

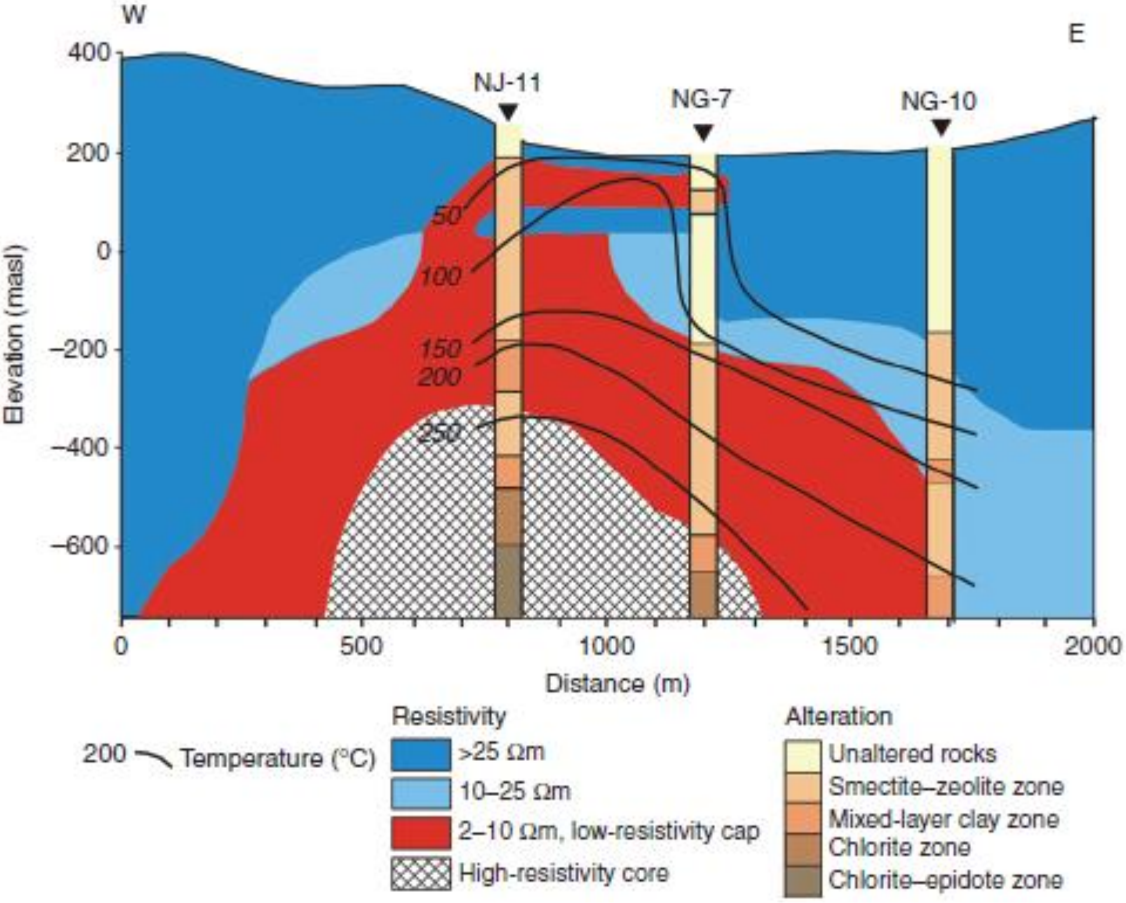

Figure 1: Typical resistivity structure of a high-temperature geothermal reservoir showing a high-resistivity core beneath a low-resistivity cap based on 2D interpretation of a detailed multimethod DC resistivity survey from 1985 and 1986. The figure also shows the alteration minerals in three wells and the isotherms derived from the estimated true formation temperature in each well based on numerous temperature logs obtained during and after drilling. The figure shows a very clear correlation between the subsurface resistivity structure, on the one hand, and the alteration mineralogy and true formation temperature, on the other hand. The section is from the Nesjavellir geothermal field, Southwest Iceland (adapted from Flóvenz et al 2012, after Árnason et al 1987b).

2. METHODS

Cation-exchange capacity (CEC) is a characteristic property of zeolites and clay minerals. For clay minerals the CEC is related to substitutions in the tetrahedral and/or octahedral sheet, which creates a charge deficit, and loss of protons at crystal edges (Christidis 2011). It is distinguished between permanent and non-permanent charges. In detail, the charge which results from structural substitutions is know as permanent charge and the charge from interrupted bonds between the structural cations and the oxygen of the OH groups of the tetrahedral and the octahedral sheet is known as the non-permanent or pH-depended charge (Christidis 2011). The layer charge is balanced by interlayer cations, like Na, Ca, K, Mg, and H, which are exchangeable (Christidis 2011).

Clay minerals show a strong preference for organic cations such as methylene blue and organo-metal complexes that have been used as index cations to determine the CEC. Due to the large size of the molecules, methods based on the adsorption of organo-metal complexes and methylene blue are not influenced by the presence of zeolites as the large molecules cannot enter the cages and channels within the zeolite structural framework (Christidis 2011). Although adsorption of methylene blue cations is routinely used for clay minerals, determination of CEC is problematic (Ammann et al 2005).

Bergaya and Vayer (1997) developed a method to determine the CEC of clay minerals by using $[Cu(en)_2]^{2+}$ (en = ethylenediamine). Meier and Kahr (1999) proposed the use of $[Cu(trien)]^{2+}$ complexes (trien = triethylenetetramine) for determination of CEC. According to Bergaya et al (2006), the use of $[Cu(en)_2]^{2+}$ or $[Cu(trien)_3]^{2+}$ complexes is presently the most versatile method for determination of CEC of clay minerals.

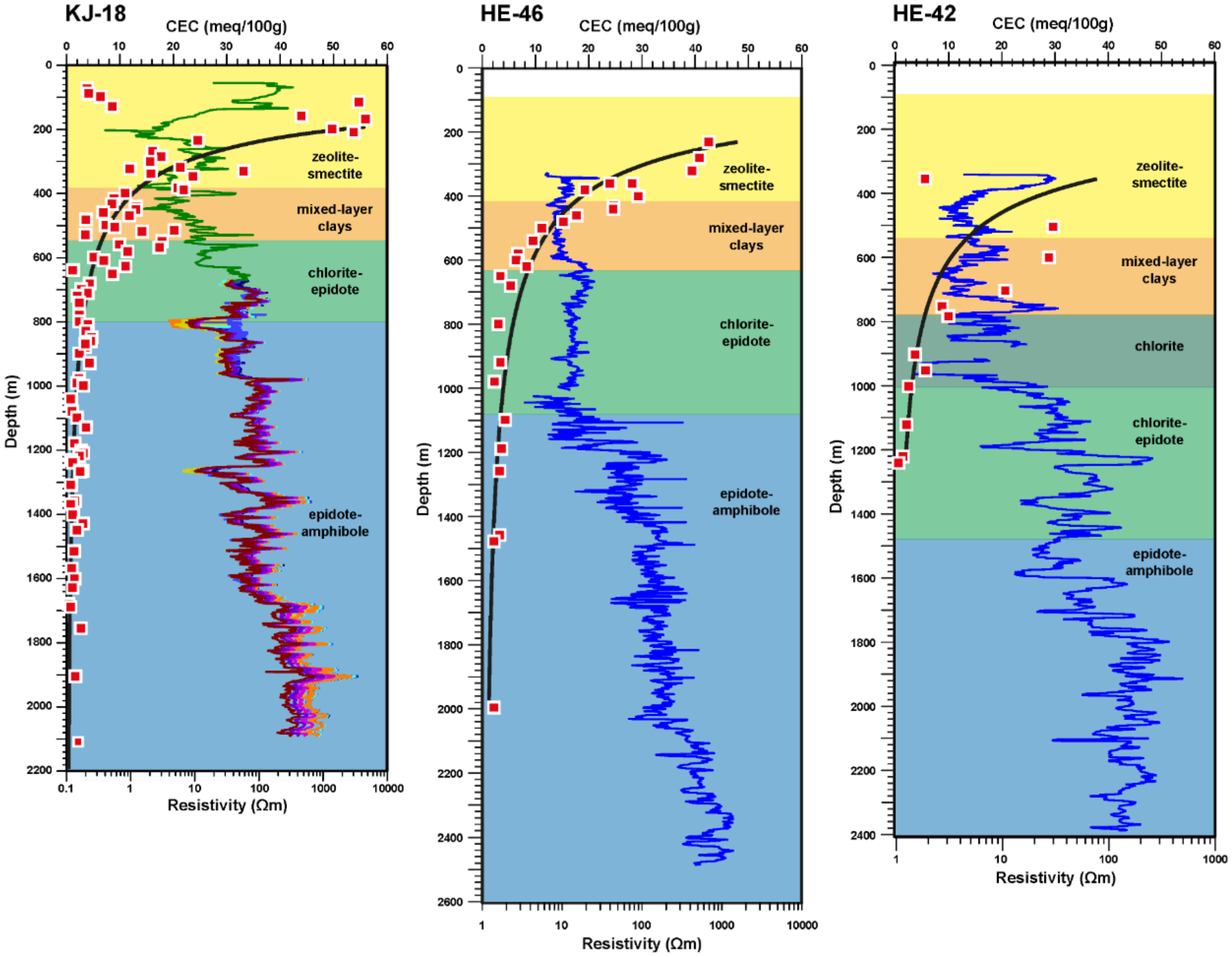

Figure 2: Depth profiles of the studied wells (HE-46 and HE-42) within the Hellisheidi geothermal system and well KJ-18 (see Figure 4 for detail) from the Krafla geothermal systems for comparison. Blue curves are electrical resistivity logs (16-inch spacing between the resistivity detectors for HE-46 and 64-inch spacing for HE-42). Red squares are CEC values and black lines are the calculated trend-lines.

For cation-exchange capacity experiments a representative aliquot of cuttings (4-5 g) from a particular depth was selected. The cuttings were washed to remove potential contamination of drilling mud and afterwards were milled by using a ball mill. Cation-exchange capacity experiments were conducted according to the method described by Meier and Kahar (1999) by using 0.01 M copper triethylenetetramine (Cu-trien). Powdered rock samples (200 mg) were dispersed into 50 mL centrifuge tubes that contained 50 mL of deionized water. Afterwards10 mL of 0.01 M Cu-trien solution were added. After 3 minutes' reaction time, the suspension was centrifuged with a micro-centrifuge for 20 minutes at 2000 rounds per minute. The supernatant solution was carefully removed from the solid fraction and the remaining Cu-trien concentration of the supernatant was measured in a spectrophotometer at a wavelength of 578 nm. The used wavelength of 578 nm differed from the wavelength (620 nm) describe in Meier and Kahar (1999), as it has been shown by other studies (e.g. Ammann et al 2005; Kaufhold and Dohrmann 2003; Steudel et al 2009; Dohrmann et al 2012) that the absorption maximum of the copper triethylenetetramine complex lies at 578 nm. Calibration of the photometer was carried out according to the calibration method described by Kaufhold (2001), by using four different Cu-trien solutions. The water content of the samples was determined by the weight loss obtained after heating the samples for 2-3 days at 105°C. The cation-exchange capacity (meq/100 g) is referred to the dry weight of the sample.

For all the wells, the samples had been selected based on the resistivity logs and lithostratigraphic succession. For well KJ-18 a total of 88 samples covering the entire depth interval were analyzed. For wells HE-42 and HE-64, 12 and 27 samples, respectively had been selected, whereas samples were primarily selected within the clay and chlorite dominated alteration zones.

3. RESULTS

3.1 KJ-18

Results of the CEC measurements for well KJ-18 are given in Figure 2. In general, the CEC values decrease with increasing depth. They mimic well the general trend of the resistivity curves. The high resistivity at shallow depth (< 120 m) coincide with low CEC values (<10 meq/100 g). High CEC values (>40 meq/100 g) concur with the low resistivity at about 200 m depth. Below that depth, the CEC values decrease exponentially and reach a steady-state level at about 1000 m depth. Below a depth of 1000 m only limited variation close to the detection limited of the CEC method appears. The elevated CEC values (>5 meq/100 g) in the shallow part of the well are in good agreement with the depth interval of the alteration zones characterized by clay minerals (Fig. 2).

For a given depth interval within the shallow part of the well (<680 m), a correlation between lithological units and CEC values is observed. For example, the high CEC values at a depth of 200 m correlates with a basaltic tuff unit, whereas the lower values below are associated with a crystalline unit. In general, high CEC values are associated with glass-rich lithologies (Stefánsson et al 1983), whereas lower CEC values are related to more crystalline lithologies (Stefánsson et al 1983). Nevertheless, the CEC between about 300 and 600 m show a large scattering. The caliper log (Stefánsson et al 1983) shows a large caving structure at about 200 m, which most likely resulted in the contamination of cuttings drilled below this structure.

The depth interval (>680 m), for which a resistivity time series during heating-up have been carried out coincide with low CEC values and shows only a very limited variation in CEC values. This variation in CEC values at a given depth cannot be synchronized to the variation in the electrical resistivity at similar depth.

Figure 3 and Figure 4 show the direct relation of the CEC of each measured sample to the electrical resistivity and conductivity, respectively, at a given depth. In general, a correlation between CEC and electrical resistivity and conductivity, respectively is observed. Nevertheless, many samples, particularly in the medium CEC range (5-30 meq/100 g) show a large scattering that results in a weak correlation.

3.2 HE-42 and HE-46

Results of the CEC measurements of well HE-42 and HE-46 are plotted along the depth profile together with the electrical resistivity logs and are presented in Figure 2. No samples from the shallow depth has been analyzed due to the missing electrical resistivity logs for both wells. The CEC decreases exponentially with increasing depth. Samples from the zeolite-smectite zone show the highest CEC values followed by samples within the mixed-layer clay and chlorite alteration zone. At the transition to the chlorite-epidote alteration zone, which are well defined by Gunnarsdóttir (2012) for well HE-42 and Snæbjörnsdóttir (2011) for well HE-46, the CEC values level out and they show only a very limited decrease with increasing depth and increasing alteration (Fig. 2).

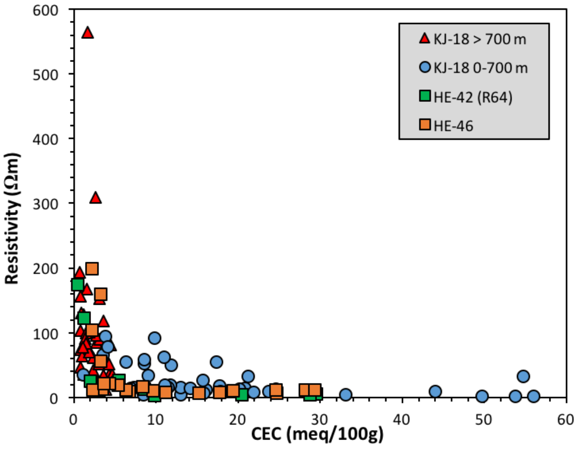

Figure 3: Correlation of the CEC results and electrical resistivity at similar given depth for wells from the Krafla and Hellisheidi geothermal systems.

For well HE-46 the transition from the mixed-layer clay to the chlorite-epidote alteration zone coincide with a sharp boundary of the electrical resistivity log (Fig. 2). At the boundary at a depth of about 600 m the electrical resistivity log shows a sharp contrast and the electrical resistivity values increase from about 8-10 Ωm to about 18-20 Ωm, but with increasing depth the electrical resistivity shows a slightly decreasing trend (Fig. 2). In detail, above 600 m the electrical resistivity curve shows only a minor variation with a more or less constant range for the electrical resistivity from ~8-10 Ωm. Within this shallow depth interval, the CEC values decrease exponentially from ~40 meq/100 g to ~6 meq/100 g with increasing depth. At the transition depth of approximately 600 m the electrical resistivity values increase to a range from ~16-20 Ωm and decrease again within a slight constant decline to ~10 Ωm at a depth of 1000 m.

Within this depth range the CEC values decrease very slightly to a minimum value of 2.1 meq/100 g.

Although the CEC results for well HE-42 show a similar trend as CEC values in wells HE-46, the electrical resistivity log differs by a stronger oscillation and slightly decreasing trend within the chlorite-epidote alteration zone.

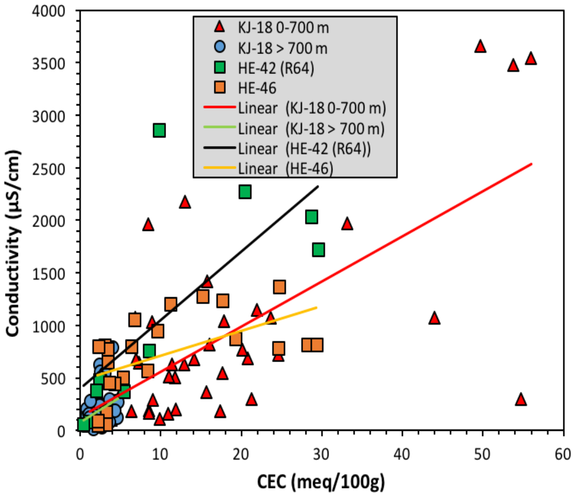

Figure 4: Correlation of the CEC results versus conductivity at similar given depth wells from the Krafla and Hellisheidi geothermal systems.

The relation of the CEC and the electrical resistivity and conductivity, respectively, at a given depth for well HE-42 and HE-46 are shown in Figure 3 and Figure 4. For both wells, the correlation of the electrical resistivity and CEC gives a very good fit. Correlation of the conductivity and the CEC shows a positive linear correlation for low CEC values. However, for higher CEC results the correlation is weak.

4. DISCUSSION

4.1 CEC and relation to alteration zones

The CEC of all studied wells show a general trend of decreasing values with increasing depth. Therefore, the sample depth can be related to a particular temperature, at which the sample is equilibrated driven by fluid-rock interaction within a hydrothermal system. This equilibration results in a change in mineralogy, which is often accompanied with a gain or loss in elements during the fluid-rock interaction (e.g. Kristmannsdóttir and Tómasson 1978; Schiffman and Fridleifsson 1991; Weisenberger and Spürgin 2009; Neuhoff et al 2000; Weisenberger and Bucher 2011). The temperature increase with increasing depth results in the formation of distinct alteration zone or metamorphic facies at higher temperature conditions (Neuhoff et al 2000; Weisenberger and Selbekk 2009).

The CEC values follow a general decreasing trend with increasing depth. This trend can be correlated directly to the mineralogical composition of the alteration zones (Fig. 2). Considering the alteration zones in a hydrothermal basaltic system (Kristmannsdóttir and Tómasson 1978; Schiffman and Fridleifsson 1991; Neuhoff et al 2000; Weisenberger and Selbekk 2009), the index minerals of individual alteration zones reflect a decrease in CEC. For example, the smectite-zeolite zone is distinguished by high CEC values of their index minerals, smectite (60-120 meq/100 g, Schiffman and Southard 1996) and zeolites species (chabazite: 390 meq/100g, Pabalan and Bertetti 2001). The mixed-layers clay zone is marked by the transition between the smectite and chlorite zone. Clay minerals in this zone consist of so call mixed-layers clays that are interstratified mixed layers of smectite and chlorite (5-15 meq/100 g, Meunier 2005), whereas with increasing temperature and depth, respectively, the mineralogical composition increase in the chlorite component of the interstratified smectite/chlorite clay (e.g. Schiffman and Fridleifsson 1991; Weisenberger and Selbekk 2009). It has been shown within petroleum system that within interstratified clays (smectite/illite) the smectite component decrease with increasing temperature and depth, respectively (Hower and Mowatt 1966; Srodon and Eberl 1987).

It can be seen in all of the studied wells (Fig. 2) that the CEC systematically decreases from the smectite/zeolites zone to the mixed layer clay zone and when entering the chlorite or chlorite-epidote alteration zone, respectively, the CEC values are below 5 meq/100 g and the trendline shows a change from an exponential trend to a linear trend. The changing trend within HE-42 and HE-46 is very well represented by the alteration zone boundary between the mixed layer clay alteration zone and the chlorite-epidote or chlorite zone. When entering the chlorite-epidote zone the CEC values are below 5 meq/100 g and the values show a very smoothly decreasing linear trend. It indicates that the mineralogical composition of the host rock is not controlled by mineral phases that exhibit a high CEC. The low CEC values in the deepest alteration zone are close to background values of the basaltic rocks (2.8 meq/100 g, Carroll 1959).

4.2 CEC vs electrical resistivity

The direct sample and depth correlation of the CEC values and the electrical resistivity follow a general trend (Fig. 3 and Fig. 4), whereas depth intervals with very high electrical resistivity coincide with low CEC and low electrical resistivity corresponds with high CEC. Although there is a relation between CEC and electrical resistivity, the direct one-to-one correlation is weak, when comparing adjacent samples within the oscillating resistivity logs (Fig. 2). For example, in well KJ-18 at the depth interval between 100 to 250 m, where thick individual lithological units appear the electrical resistivity and CEC show a good one-to-one correlation. Nevertheless, below 250 m, where cutting analysis indicate that the lithological profile consists of a sequence of thin individual lithological units (each less than 10 m thickness) a direct one-to-one correlation is very weak or even absent as seen at the depth interval between 350 and 450 m, and 550 and

620 m. However, it should be kept in mind that there is a large uncertainty in the cutting origin and depth. In contrast to the resistivity data, which has a resolution on a cm scale, cuttings are sampled during drilling in a 2-meter interval. The long traveling time of the cuttings from the location of drilling to the surface, cross contamination and mixing affects, and possible human errors may cause a large uncertainty of the sample origin and depth and therefore the sample depth are biased. In particular, within stratigraphic sequence of thin lithological units and resulting resistivity patterns with a small oscillation pattern, the correlation between CEC and electrical resistivity should be considered with a large bias.

4.3 Resistivity structure of high-temperature fields and relation to the CEC

High-temperature geothermal fields within volcanic areas of the world have in general a similar electrical resistivity structure (Flóvenz et al 2012). Figure 1 shows a typical resistivity cross section from the Nesjavellir high-temperature geothermal system within the Hengill volcanic system in SW Iceland (Árnason et al 1987b). The lithological inventory is almost entirely composed of rocks of basaltic composition and include lavas, scoria, hyaloclastites, and intrusions, whereas no correlation is detected between the surface resistivity and the basaltic lithology in the boreholes (Flóvenz et al 2012).

A pilot study by Árnason et al (1987b) showed that within the Nesjavellir geothermal system there is a low-resistivity cap over-coating an up-doming resistivity core (Fig. 1). Comparing the depth interval of the low-resistivity cap and the alteration zones derived from cuttings analysis during drilling showed that the low-resistivity cap coincides with the smectite alteration zone, whereas the high-resistivity core coincide the chlorite alteration zone.

Studies of CEC on all three selected wells show that the low-resistivity at shallow depth is associated with a CEC above a critical value of about 5 meq/100 g (Fig. 2). In particular, in well HE-46 the prompt increase in electrical resistivity at the facies boundary between mixed-layer clay and chlorite epidote alteration coincides with the critical threshold of 5 meq/100 g.

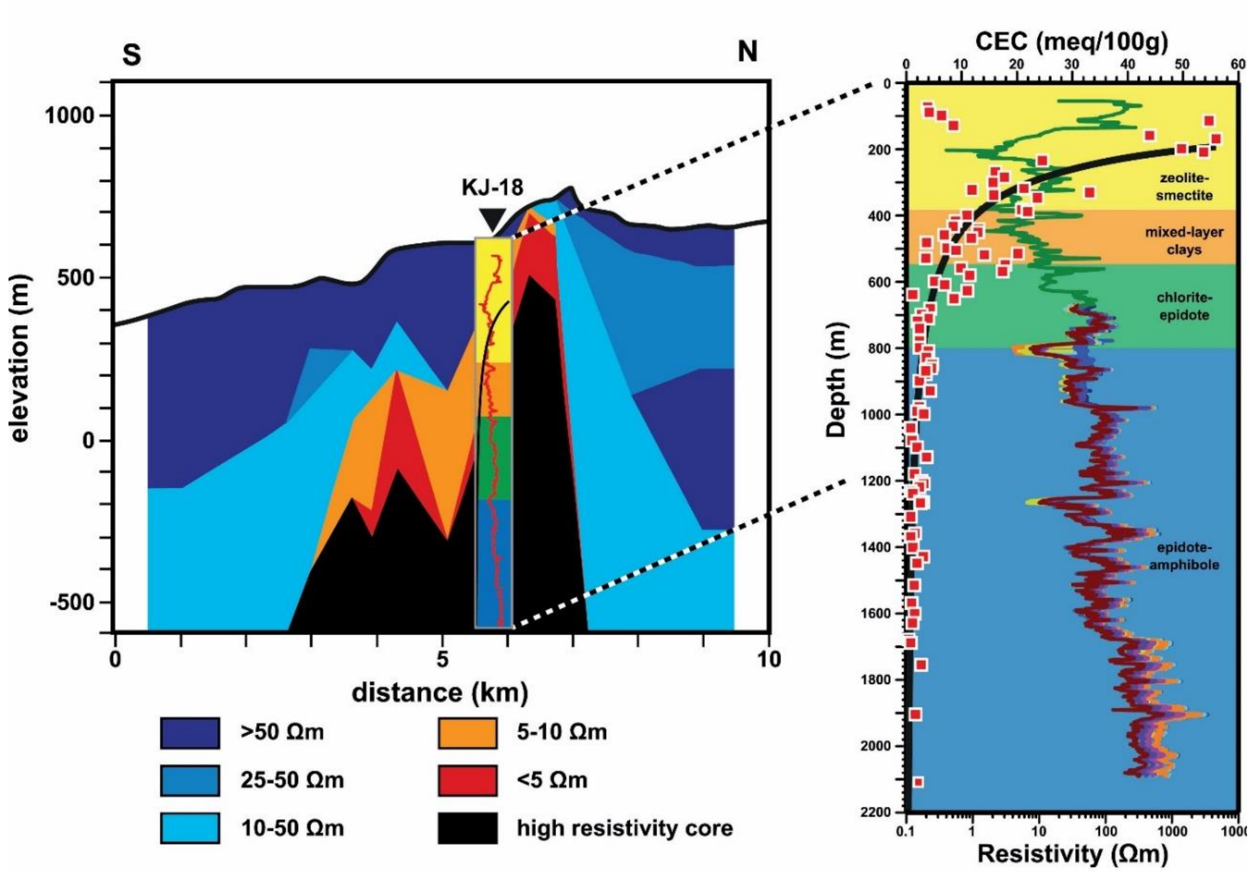

Figure 5: North-south profile of the resistivity structure of a high-temperature geothermal reservoir within the Krafla geothermal system, northeast Iceland and the location of the studied well KJ-18 is given including the resistivity log trend-line of the CEC results. The more detailed log profile of well KJ-18 is given to the right. The resistivity structure is based on 1D-inversion modelling TEM soundings adapted from Árnason and Magnússon (2001).

Figure 5 shows a north-south profile of the resistivity structure of a high-temperature geothermal reservoir within the Krafla geothermal system, in northeast Iceland that is based on 1D-inversion modeling of surface resistivity data (TEM) that was carried out in a dense grid (Árnason and Magnússon 2001). In addition, the location of well KJ-18 is given and the electrical resistivity log and results of the CEC is shown. The figure shows a clear correlation of the modeled surface resistivity, electrical resistivity log, mineral alteration and CEC. High CEC values are observed within the shallow part (120-700 m) and at a similar depth interval the low-resistivity core (red and orange colors) was identified by surface resistivity measurements (Árnason and Magnússon 2001). Within the high-resistivity core the CEC values are below 5 meq/100 g. The higher resistivity zone seen in the surface resistivity and the electrical resistivity log at shallow depth (<120 m) is characterized by low CEC values. Flóvenz et al (1985) related this resistivity contrast at the top of the smectite zone to the onset of interface conduction in the rock.

The clear correlation between resistivity model based on surface soundings, resistivity logs and host rock alteration, in particular the formation of clay minerals within a specific depth interval, confirms the model by Árnason et al (1987a, b) that was predicted for the Nesjavellir geothermal system (Fig. 1).

5. CONCLUSIONS

Cation-exchange capacity analysis of three wells within high-temperature geothermal systems in Iceland reveal a similar trend for the CEC values with increasing depth. The CEC values are highest within the smectite alteration zone and the CEC values decrease exponentially with increasing depth down to the facies boundary between the mixed-layer clays and chlorite-epidote or chlorite alteration zones (Fig. 2). At this depth the CEC values are <5 meq/100g, except for well KJ-18, where the transition is slightly deeper. Within the epidote-dominated alteration zone the CEC values decrease linearly with increasing depth. The depth interval with high CEC values (>5 meq/100g) coincides with the low resistivity based on resistivity logs and confirms the hypothesis by Flóvenz et al (2012): *´The increase in resistivity from the smectite alteration zone to the chlorite zone is likely due to the higher CEC of smectite, as compared with chlorite´.*

In general, samples that are characterized by high CEC values coincide with low-resistivity interval of the resistivity logs and samples with low CEC are characterized by high-electrical resistivity based on resistivity logs. However, no one-to-one correlation is possible for samples with medium CEC values, which is most likely due to the uncertainty in cutting origin and possible cross contamination.

A good correlation is seen when comparing the surface resistivity model within the Krafla geothermal system, and the resistivity log and the results of the CEC measurements within well KJ-18 (Fig. 5). This confirms the resistivity model by Árnason et al (1987b).

REFERENCES

Árnason, K., Flóvenz, Ó.G., Georgsson, L. and Hersir, G.P.: Resistivity structure of high temperature geothermal systems in Iceland, *International Union of Geodesy and Geophysics (IUGG) XIX General Assembly*, Vancouver, BC, Canada, (1987a), abstract V, 477.

Árnason, K., Haraldsson, G.I., Johnsen, G.V., Thorbergsson, G., Hersir, G.P., Saemundsson, K., Georgsson, L.S., Rögnvaldsson, S.Th. and Snorrason, S.P.: Nesjavellir-Ölkelduháls, surface exploration, *Orkustofnun, Reykjavík*, Report OS-87018/JHD-02 (in Icelandic), (1987b).

Árnason, K. and Flóvenz, Ó.G.: Evaluation of physical methods in geothermal exploration of rifted volcanic crust, *Geothermal Resources Council, Transcations*, **16**, (1992), 207-214.

Árnason, K. and Magnússon, I.Þ.: Niðurstöður viðnámsmælinga í Kröflu, *Orkustofnun, Reykjavík*, Report OS-2001/062 (in Icelandic), (2001).

Ammann, L., Bergaya, F. and Lagalym, G.: Determination of the cation exchange capacity of clays with copper complexes revisited, *Clay Minerals*, **40**, (2005), 441-453.

Bergaya, F. and Vayer, M.: CEC of clays: Measurement by adsorption of a copper ethylenediamine complex, *Applied Clay Science*, **12**, (1997), 275-280.

Bergaya, F., Lagaly, G. and Vayer, M.: Cation and anion exchange, in: Handbook of clay science, Bergaya, F., Theng, B.K.G. and Lagaly, G. (Ed.), 979 – 995, *Elsevier Ltd.*, Netherlands, (2006).

Carroll, D.: Ion exchange in clays and other minerals, *Geological Society of America Bulletin*, **70**, (1959), 749-779.

Christidis, G.E.: Industrial clays, in: Advances in the Characterization of Industrial Minerals, Christidis G.E. (Ed.), 341-414, *EMU Notes in Mineralogy*, **9**, (2011).

Dohrmann, R., Genske, D., Karnland, O., Kaufhold, S., Kiviranta, L., Olsson, S., Plötze, M.; Sandén, T., Sellin, P., Svensson, D. and Valter, M.: Interlaboratory CEC and exchangeable cation study of betonite buffer materials: I. Cu(II)-triethylenetetramine method, *Clays and Clay Minerals*, **60**, (2012),162-175.

Flóvenz, Ó.G., Georgsson, L.S. and Árnason, K.: Resistivity structure of the upper crust in Iceland, *Journal of Geophysical Research*, **90-B12**, (1985), 10136–10150.

Flóvenz, Ó.G., Hersir, G.P., Sæmundsson, K., Ármannsson, H. and Friðriksson, Þ.: Geothermal Energy Exploration Techniques, in: Comprehensive Renewable Energy, Sayigh, A. (Ed.), 51–95, *Elsevier*, Oxford, **7**, (2012).

Gunnarsdóttir, S.H.: Jarðfræði og ummyndun í nágrenni Reykjafells á Hellisheiði, *MSc thesis*, University of Iceland (in Icelandic), (2012).

Haraldsóttir, S.H. and Franzson, H.: Viðnám á suðurhluta Hengilssvæðis. Samanburður borholumælinga, niðurstaðna úr TEM-MT og ummyndunar, ÍSOR, Iceland GeoSurvey report 2011/075 (in Icelandic), (2011).

Hower, J. and Mowatt, T.C. The mineralogy of illites and mixed-layer illite/montmorillonites, *American Mineralogist*, **51**, (1966), 825-854.

Kaufhold, S.: Untersuchungen zur Eignung von natürlich alterierten sowie mit Oxalsäure aktivierten Bentoniten als Bleicherde für Pflanzenöle, PhD thesis, RWTH Aachen (in German), (2001).

Kauhold, S. and Dohrmann, R.: Beyond the Methylene Blue Method: Determination of the Smectite Content using the Cutriene Method, *Zeitschrift für Angewandte Geologie*, **49**, (2003), 13-17.

Kristmannsdóttir, H. and Tómasson, J.: Zeolites zones in geothermal areas in Iceland, in: Natural zeolites; occurrence, properties, use, Sand, L.B. and Mumpton, F.A. (Ed.), 277–284, *Pergamon Press*, New York, (1978).

Meier, L.P. and Kahr, G.: Determination of the Cation Exchange Capacity (CEC) of Clay Minerals Using the Complexes of Copper(II) Ion with Triethylenetetramine and Tetraethylenepentamine, *Clays and Clay Minerals*, **47**, (1999), 386-388.

Meunier, A.: Clays, *Springer*, Berlin, (2005).

Neuhoff, P.S., Fridriksson, T. and Bird, D.K.: Zeolite parageneses in the North Atlantic Igneous Provinces: implications for geotectonics and groundwater quality of basaltic crust, *International Geological Review*, **42**, (2000), 15–44.

Pabalan, R.T. and Bertetti, F.P.: Cation-Exchange Properties of Natural Zeolites, *Reviews in Mineralogy and Geochemistry*, **45**, (2001), 453-518.

Schiffman, P. and Fridleifsson, G.O.: The smectite-chlorite transition in drillhole NJ-15, Nesjavellir geothermal field, Iceland: XRD, BSE and electron microprobe investigations, *Journal of Metamorphic Geology*, **9**, (1991), 679–696.

Schiffman, P. and Southard, R.J.: Cation exchange capacity of layer silicates and palagonitized glass in mafic volcanic rocks; a comparative study of bulk extraction and in situ techniques, *Clays and Clay Minerals*, **44**, (1996), 624-634.

Snæbjörnsdóttir, S.Ó.: Jarðfræði og jarðhitaummyndun við vesturjaðar sigdældar Hengils, *MSc thesis*, University of Iceland (in Icelandic), (2011).

Sordorn, J. and Eberl, D.D.: Illite, *Reviews in Mineralogy and Geochemistry*, **13**, (1984), 495-544.

Stefánsson, V., Guðmundsson, Á., Steingrímsson, B., Guðmundsson, G., Friðleifsson G.Ó., Axelsson, G., Ármannsson, H., Sigvaldason, H., Benjamínsson, J. and Sigurðsson, Ó.: Krafla, hola KJ-16, 17 and 18. Rannsóknir samhliða borun og vinnslueiginleikar. *Unpublished manuscript, (1983).*

Steudel, A., Weidler, P., Schuhmann, R. and Emmerich, K.: Cation exchange reactions of vermiculite with Cu-triethylenetetramine as affected by mechanical and chemical pretreatment, *Clays and Clay Minerals*, **57**, (2009), 405-412.

Weisenberger, T. and Selbekk, R.S.: Multi-stage zeolite facies mineralization in the Hvalfjördur area, Iceland, *International Journal of Earth Sciences*, **98**, (2009), 985-999.

Weisenberger T. and Spürgin, S.: Zeolites in alkaline rocks of the Kaiserstuhl volcanic complex, SW Germany - new micropobe investigation and their relationship to the host rock, *Geologica Belgica*, **12**, (2009), 75-91.

Weisenberger, T. and Bucher, K., Mass transfer and porosity evolution during low temperature water-rock interaction in gneisses of the Simano nappe: Arvigo, Val Calanca, Swiss Alps, *Contributions to Mineralogy and Petrology*, **162**, (2011), 61-81.

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